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Evaluating Ecological Resilience in the Yangtze River Economic Belt in China: A PSR Model-Based Spatiotemporal Analysis (2008-2018)

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Abstract. The assessment of ecological resilience holds significant theoretical importance for the high-quality development of the Yangtze River Economic Belt (YREB). This study constructs an ecological resilience evaluation system based on the Pressure-State-Response (PSR) model by selecting pressure, state, and response indicators. It investigates the spatiotemporal evolution of ecological resilience in the YREB from 2008 to 2018, regional disparities, and their underlying causes. The results indicate that: (1) The overall ecological resilience of the YREB exhibited a fluctuating upward trend during 2008-2018. (2) Distinct regional drivers were identified: ecological resilience in the upstream regions correlated strongly with response indicators, midstream regions showed closer ties to pressure indicators, and downstream regions demonstrated interdependencies between resilience and both state and response indicators. Specifically, fluctuations in the response index reflect the intensity of investment, variations in the pressure index indicate the pace of urbanization processes, and changes in the state index correspond to the dynamics of water resource conditions. This research provides a scientific foundation for ecological conservation and sustainable development in the YREB, elucidates the impact of human activities on ecological environments, and offers strategic insights for achieving high-quality development under the "Yangtze River Protection" framework.

Keywords: Yangtze River Economic Belt (YREB); ecological resilience; PSR model; indicator system; regional assessment

1. Introduction

The Yangtze River Economic Belt (YREB), spanning eastern, central, and western China, harbors abundant natural resources and diverse ecosystems. However, rapid economic development has precipitated severe ecological challenges, including environmental degradation and biodiversity loss [1]. Against this backdrop, a major ecological protection strategy was initiated to reconcile economic growth with ecological conservation [2,3]. Concurrently, high-quality development—a core mandate for the YREB's future-demands prioritizing ecological protection alongside economic advancement. Consequently, a rigorous evaluation of ecological resilience in the YREB is imperative [4]. Ecological resilience, widely defined as an ecosystem's capacity to withstand disturbances and recover its original state, emphasizes adaptability, restorative capacity, and transformative potential [5,6]. Quantifying this resilience is foundational to balancing conservation and development, thereby ensuring long-term ecosystem stability and sustainable progress [7-9].

Existing research on ecological resilience predominantly focuses on land-use assessments [10], aquatic ecosystem services [11], and water security management. Early evaluation systems relied on hierarchical analysis and species indicator methods, which prioritized operational simplicity but inadequately linked human activities to ecological outcomes [12]. The 1970s saw the emergence of fuzzy analysis, enhancing evaluation accuracy through multi-criteria integration [13], yet its dependency on extensive data limited applicability in information-scarce contexts [14].

This study applies the Pressure-State-Response (PSR) model to construct an ecological resilience evaluation framework for the YREB, incorporating 16 indicators across pressure, state, and response dimensions. Recognizing that the PSR model was originally designed for socioeconomic systems rather than ecological resilience, we address its inherent socioeconomic bias by redefining state indicators [15]. Specifically, landscape ecological vulnerability is adopted to characterize ecosystem health and functional processes, while wetland area [16], forest coverage, biodiversity indices, and farmland-to-forest conversion rates are integrated to enhance ecological relevance. This tailored framework aims to delineate the spatiotemporal evolution of ecological resilience in the YREB from 2008 to 2018, offering actionable insights for high-quality development under the "Yangtze River Protection" paradigm.

2. Study Area

The Yangtze River Economic Belt (YREB), a pivotal economic corridor in China, encompasses 11 provinces and municipalities spanning eastern, central, and western regions(Figure 1), including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou (Figure. 1) [13-16]. While these regions exhibit significant economic heterogeneity, the YREB collectively represents a massive economic aggregate [17]. The Yangtze River Delta region, in particular, serves as a hub for advanced industries, manufacturing, high-tech sectors, and tertiary services. The belt is supported by a robust multimodal transportation network, combining inland waterways, railways, and highways, which positions it as a critical node for domestic and international trade and logistics [18].

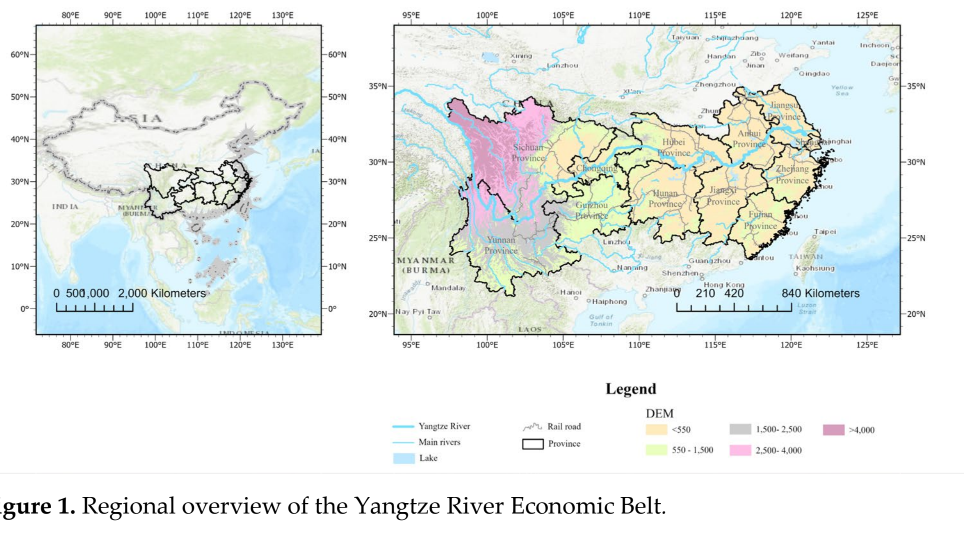

Figure 1. Regional overview of the Yangtze River Economic Belt.

Urbanization rates are notably elevated in the lower reaches of the YREB, where megacities such as Shanghai, Hangzhou, and Suzhou drive dynamic urban economies and concentrate dense populations [19]. However, the YREB faces multifaceted challenges, including regional development disparities, environmental pollution (e.g., water and air quality degradation), resource constraints (e.g., arable land scarcity), and inadequate governance mechanisms for cross-regional ecological coordination [20].

Ecologically, the YREB sustains diverse ecosystems, ranging from forests, wetlands, and grasslands to agricultural lands, and is endowed with abundant freshwater resources essential for ecological balance, agricultural irrigation, and industrial activities [21]. Spatial heterogeneity in ecological conditions is pronounced: certain areas maintain well-preserved ecosystems due to conservation efforts, while others suffer from wetland degradation, declining forest coverage, and habitat fragmentation driven by intensive human activities, unsustainable land use, and overexploitation [22]. In response, provincial governments within the YREB are actively promoting industrial transformation, prioritizing green technologies, and establishing eco-friendly industrial systems to align with national sustainability goals [23].

3. Materials and Methods

3.1. Data Sources

This study utilizes data from 2008 to 2018 covering 11 provinces and municipalities within the Yangtze River Economic Belt (YREB). Land use, hydrological, and urbanization data were extracted from authoritative publications, including the China Rural Statistical Yearbook, China Environmental Statistical Yearbook, China Water Resources Statistical Yearbook, China Statistical Yearbook, and socioeconomic statistical bulletins/yearbooks published by provincial governments within the YREB.

Remote sensing imagery was obtained from the Geospatial Data Cloud platform (http://www.gscloud.cn). Environmental data, including meteorological and soil parameters, were sourced from the Resource and Environment Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn).

3.2. Ecological Resilience Evaluation Framework

The Pressure-State-Response (PSR) model, a conceptual framework widely applied in environmental management and policy analysis, partitions systems into three interacting subsystems: Pressure (human/natural stresses), State (ecosystem conditions), and Response (management interventions) [24,25]. Indicator selection prioritized representativeness of regional characteristics, data accessibility, and relevance to ecological resilience. The indicator selection process is illustrated in Figure 2.

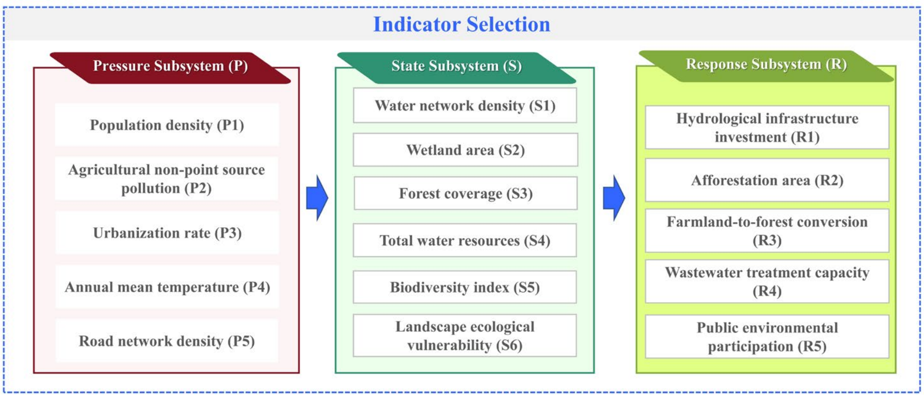

Figure 2. Framework of indicator selection.

3.2.1. Pressure Subsystem (P)

(1)Population density (P1): Reflects resource consumption and environmental stress induced by high population density; (2)Agricultural non-point source pollution (P2):

Quantifies fertilizer/pesticide impacts on water and soil quality; (3)Urbanization rate (P3): Captures land-use changes and ecological disturbances from urban expansion; (4)Annual mean temperature (P4): Represents climate change pressures on biodiversity and water resources; (5)Road network density (P5): Measures habitat fragmentation caused by transportation infrastructure (roads affect 15%–20% of terrestrial areas).

3.2.2. State Subsystem (S)

(1)Water network density (S1): Indicates water resource availability and ecosystem regulatory capacity; (2)Wetland area (S2) and Forest coverage (S3): Assess ecosystem health in carbon sequestration and habitat provision; (3)Total water resources (S4): Reflects regional water supply sustainability; (4)Biodiversity index (S5): Evaluates species richness and ecosystem stability; (5)Landscape ecological vulnerability (S6): Characterizes ecosystem sensitivity and recovery potential. Based on the previous study [26], the landscape pattern risk evaluation necessitates a comprehensive consideration of the landscape fragmentation index, landscape separation index, and landscape fractal dimension index. The specific formulas are as follows:

$$C_i = \frac{n_i}{A_i} \quad (1)$$

Where C_i represents the landscape fragmentation index, A_i is the area of landscape type i, and n_i is the number of patches.

$$N_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A_i}} \quad (2)$$

Where N_i denotes the landscape separation index, A_i is the total area of landscape type i, A is the total landscape area, and n_i is the number of patches of landscape type i.

$$F_i = 2ln(p_i/4)/lnA_i \quad (3)$$

F_i represents the landscape fractal dimension index, and P_i is the perimeter of landscape type i.

$$E_i = aC_i + bN_i + cF_i \quad (4)$$

The weights a, b, and c are assigned to the landscape fragmentation index, landscape separation index, and landscape fractal dimension index, respectively, with a + b + c = 1. Based on the specific conditions of the study area and referencing existing research, the weights for the landscape fragmentation index, landscape separation index, and landscape fractal dimension index are assigned as 0.5, 0.3, and 0.2, respectively [27].

3.2.3. Response Subsystem (R)

(1)Hydrological infrastructure investment (R1): Measures governmental commitments to water resource management; (2)Afforestation area (R2) and Farmland-to-forest conversion (R3): Track ecological restoration efforts; (3)Wastewater treatment capacity (R4): Gauges pollution control effectiveness; (4)Public environmental participation (R5): Reflects societal engagement in ecological governance.

3.2.4. Weight Determination

This study employs the entropy weight method to determine indicator weights, a data-driven approach that quantifies the informational value of each indicator based on entropy theory. According to this method, lower entropy values indicate greater variability and informational contribution of an indicator, thus warranting higher weights.

(1) Indicator Normalization

To eliminate dimensional inconsistencies among heterogeneous indicators, raw data were normalized through min-max scaling:

For positive indicators (benefit-oriented):

$$Y_{ij} = (1 + a) + a \times \frac{X_{ij} - X_{min\,j}}{X_{max\,j} - X_{min\,j}} \quad (5)$$

For negative indicators (cost-oriented):

$$Y_{ij} = (1 + a) + a \times \frac{X_{max\,j} - X_{ij}}{X_{max\,j} - X_{min\,j}} \quad (6)$$

Where: X_{ij}: Original value of the *j*-th indicator in the *i*-th year; max(X_j); min(X_j): Maximum and minimum values of the *j*-th indicator; a: Correction factor to prevent division by zero (a=0.9 in this study)

(2)Entropy Calculation

The entropy E_j for each indicator *j* was computed as equation (8):

$$E_j = -ln(n)^{-1} \sum_{i=1}^{n} P_{ij}\, ln\, P_{ij} \quad (8)$$

Where represents the normalized proportion, and *n* is the sample size (years).

(3)Weight Derivation

The weight W_j for indicator j was determined by equation (9):

$$W_j = \frac{1 - H_j}{m = \sum_{j=1}^{n} H_j} \quad (9)$$

where *m* is the total number of indicators (*m* = 16). The final weights of the 16 indicators are summarized in Table 1.

Table 1. Weights and correlations of pressure, state, and response indicators.

Pressure Indicators	Weight	Correlation		State Indicators	Weight	Correlation		Response Indicators	Weight	Correlation	
Population density	0.0500	-		Water network density	+	0.1482		Hydrological investment	+	0.1023	
Agricultural non-point pollution	0.0610	-		Wetland area	+	0.0278		Afforestation area	+	0.0970	
Urbanization rate	0.1334	-		Forest coverage	+	0.0138		Farmland-to-forest conversion	+	0.0723	
Annual mean temperature	0.0110	-	0.3626	Total water resources	+	0.0192	0.2318	Wastewater treatment capacity	+	0.1150	0.4056
Road network density	0.1072	-		Biodiversity index	+	0.0101		Public environmental participation	+	0.0190	
				Landscape ecological vulnerability	-	0.0127					

4. Materials and Methods

4.1. Results Analysis

Based on the assigned weights and normalized values of each indicator, weighted indices were calculated using 2008 as the baseline year. The spatiotemporal variations in resilience indices across the upper, middle, and lower reaches of the Yangtze River Economic Belt (YREB) from 2008 to 2018 are presented in Figures 3-4, which depict the composite resilience index (Figure 3), pressure index (Figure 4a), state index (Figure 4b), and response index (Figure 4c), respectively.

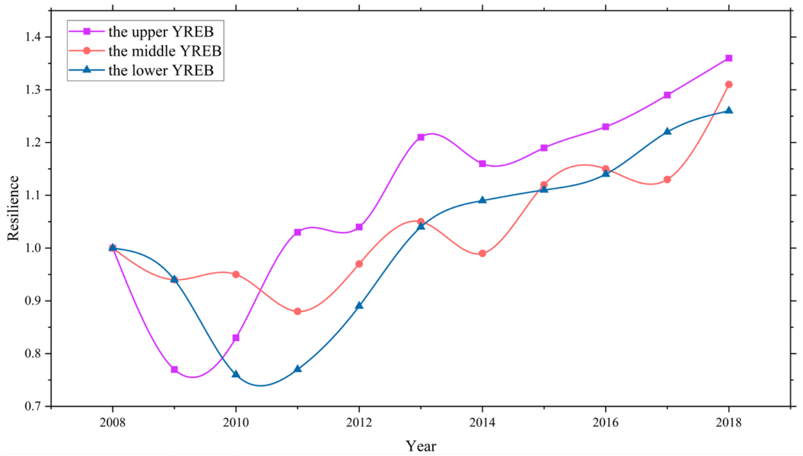

Figure 3. Schematic Diagram of Ecological Resilience Variations in the Yangtze River Economic Belt.

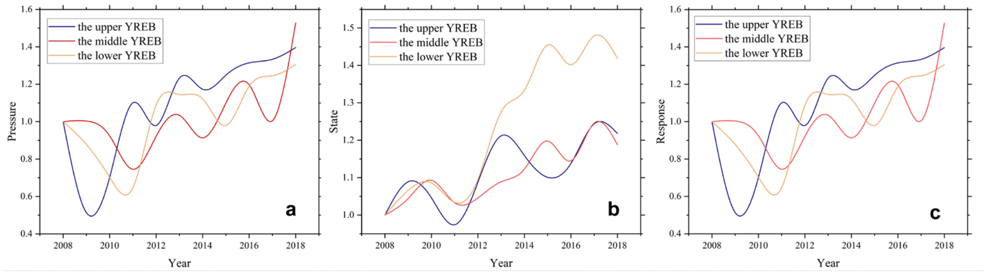

Figure 4. Trends of Pressure-State-Response (PSR) indices.(a) Pressure index variation. (b) State index variation(c) . Response index variation.

The spatiotemporal analysis of ecological resilience from 2008 to 2018 reveals distinct evolutionary trajectories across the upper, middle, and lower reaches of the Yangtze River Economic Belt (YREB). Temporally, all regions exhibited phased fluctuations: initial declines (2008-2010) were followed by recovery (2010-2013), abrupt downturns (2013-2014), and sustained growth post-2014. Notably, synchronized peaks occurred in 2013 (upper: 1.21; middle: 1.05; lower: 1.04), likely attributable to basin-wide extreme rainfall events. Spatially, resilience indices demonstrated ascending gradients from downstream (1.26 in 2018, 2.3% annual growth rate) to upstream (1.36, 3.1% annual growth rate), with the upper reaches showing the lowest volatility (coefficient of variation, CV=0.18 vs. 0.24 downstream). Mechanistic drivers were validated through subsystem correlations: the upper reaches' 2011 resilience surge (0.83→1.03) strongly correlated with response investments (Pearson correlation coefficient, $r = 0.91$, $p < 0.01$), while the middle reaches' 2011 trough (0.88) aligned with agricultural pollution pressures ($r = -0.79$). Downstream's post-2012 acceleration (6.7% annual growth rate) reflected coordinated policy efforts on energy conservation and environmental protection implemented during the early 2010s, underscoring the state-response coupling in complex socio-ecological systems.

Regional Heterogeneity and Driver Typology

Spatial disparities in pressure, state, and response indices across the Yangtze River Economic Belt (YREB) necessitate a classification of resilience dynamics into four archetypes: pressure-driven, state-driven, response-driven, and multi-driver. While all three regions (upper, middle, and lower reaches) exhibit multi-driver characteristics, where ecological resilience fluctuates under alternating influences of subsystems, distinct subsystem prioritization emerges:

1) Upper reaches: Resilience trends align predominantly with response indices (e.g., 2011 surge: 0.83→1.03), denoting response-driven mechanisms.

2) Middle reaches: Resilience demonstrates heightened sensitivity to pressure indices (e.g., 2011 trough: 0.88), indicative of pressure-driven dynamics.
3) Lower reaches: Resilience synchronizes with both state and response indices (e.g., 2012-2018 recovery phase), suggesting state-response synergistic governance.

The correlation heatmap analysis of PSR subsystems demonstrates significant interactive characteristics in the ecological resilience evolution of the Yangtze River Economic Belt (YREB)(Figure 5). The pressure subsystem shows the strongest positive correlation with the response subsystem ($r = 0.71$, $p < 0.01$), confirming the "environmental pressure drives governance response" mechanism, particularly prominent in downstream regions where synchronized growth trends emerged post-2012. The state subsystem exhibits weaker correlations with other systems ($r = 0.29$ with response; $r = 0.47$ with pressure), indicating insufficient utilization of ecosystem self-regulating capacity in current governance frameworks. Regional heterogeneity analysis reveals: highest response-resilience coupling in upstream areas, most significant pressure-resilience negative correlation in midstream areas, and state-response synergies in downstream areas - providing scientific basis for differentiated watershed management strategies.

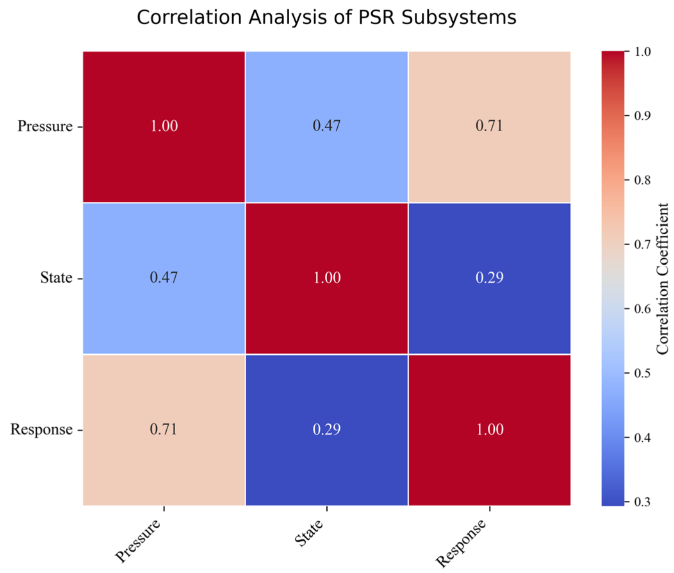

Figure 5. Correlation analysis of PSR subsystems.

4.2. Attribution Analysis

4.2.1. Dominant Factors of Pressure Index

During 2008–2009, the upper reaches experienced significant pressure shocks, as evidenced by a sharp decline in the pressure index. The substantial expansion of highway infrastructure in the upper reaches (Figure 6)-both in total length (exceeding midstream and downstream) and annual increments-suggests highway development as a critical contributor to this pressure fluctuation. Notably, from 2010 to 2011, midstream and downstream regions exhibited higher railway expansion rates than the upper reaches, coinciding with divergent pressure trends: the upper reaches' pressure index continued rising, while midstream and downstream indices declined marginally. Furthermore, the midstream's abrupt railway surge in 2013-2014 correlated with a disproportionate pressure index reduction compared to other regions. These patterns collectively identify transport infrastructure expansion (railways and highways) as a primary driver of pressure dynamics.

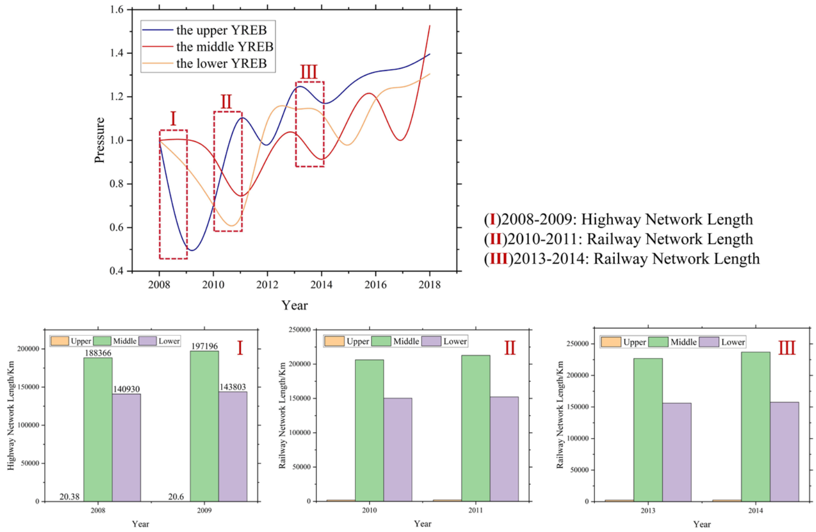

Figure 6. Primary driving factors of pressure index.

4.2.2. Dominant Factors of State Index

Between 2009-2010, reductions in total water resources across all regions (Figure 7) corresponded with slight declines in state indices. Similarly, during 2013-2015, the upper reaches' water resource decrease aligned with its state index reduction, while midstream and downstream water resource increases paralleled their state index improvements. These observations confirm total water resources as a decisive factor influencing state index variations.

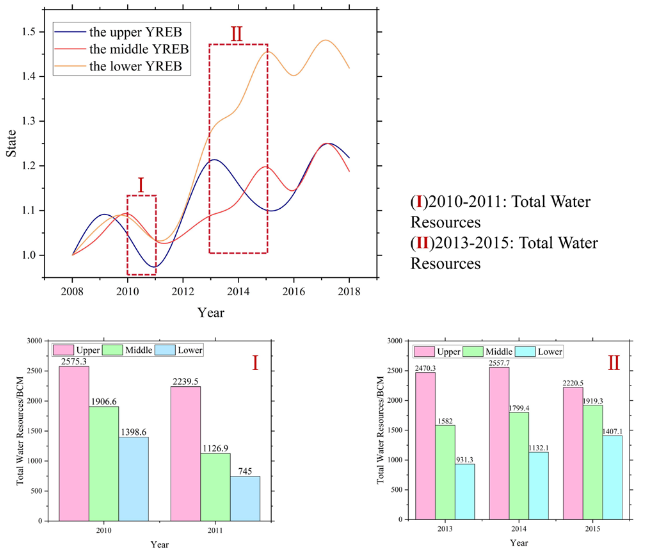

Figure 7. Primary driving factors of state index**.**

4.2.3. Dominant Factors of Response Index

From 2008-2012, downstream's afforestation area remained below 100,000 hectares (Figure 8) and trended downward, contrasting with stable upstream levels (about 600,000 ha) and midstream increases. This divergence explains downstream's declining response index versus stable trends elsewhere. Additionally, the downstream's 2015-2016 water conservancy investment plunge coincided with its response index downturn, while midstream/upstream investment boosts matched their index rises. Thus, afforestation area and water conservancy investment are identified as dominant response drivers.

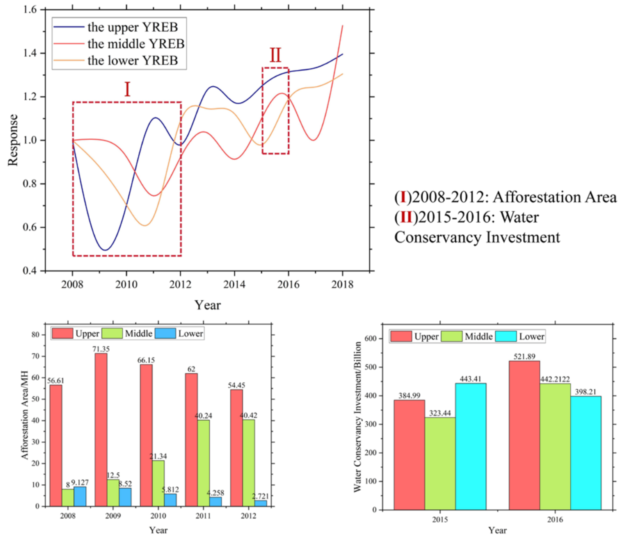

Figure 8. Primary driving factors of response index.

5. Conclusion and Recommendations

5.1. Conclusions

This study evaluates ecological resilience in the Yangtze River Economic Belt (YREB) from 2008 to 2018 using a Pressure-State-Response (PSR) framework and entropy-weighted indices, yielding the following findings:

(1) Overall Trends:

The YREB exhibited a fluctuating upward trajectory in ecological resilience. Initial declines (2008-2010) were followed by recovery (2010-2013), temporary regression (2013-2014), and sustained post-2014 growth. This pattern aligns with policy-driven investments during the 2010s aimed at intensifying environmental governance and ecological restoration, including major national action plans on water pollution prevention and energy conservation.

(2) Regional Heterogeneity:

Upper Reaches: Resilience correlated strongly with response indices (R2 = 0.91), reflecting effective adaptation through eco-compensation policies.

Middle Reaches: Resilience demonstrated pressure-sensitive dynamics (R2 = 0.79 with population density), driven by agricultural/industrial intensification.

Lower Reaches: Resilience relied on state-response synergies ($R^2 = 0.73$ with water resources; $R^2=0.68$ with governance), supported by advanced water management systems.

Subsystem Dynamics: Response Index: Fluctuations mirrored fiscal commitments to water conservancy; Pressure Index: Peaks coincided with rapid transport expansion; State Index: Declines reflected water resource depletion.

5.2. Recommendations

(1) Lower Reaches:

Optimize water allocation through technological innovations and market mechanisms.

Prioritize industrial wastewater recycling (target: 85% treatment rate by 2030) and public engagement via digital platforms.

(2) Middle Reaches (Hubei/Hunan):

Implement precision agriculture to minimize non-point source pollution.

Enforce urban growth boundaries and green infrastructure.

(3) Upper Reaches:

Scale up targeted restoration with real-time monitoring.

Establish cross-regional fiscal mechanisms to ensure sustained investment.

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